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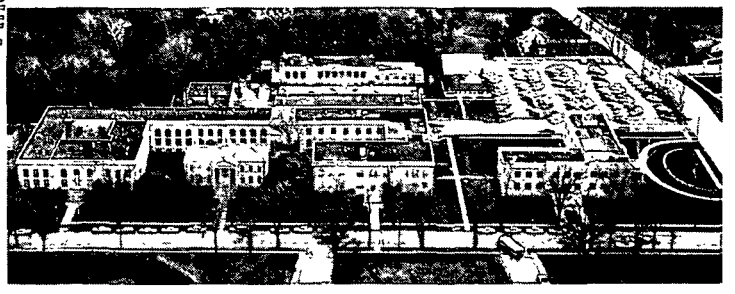

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DENSITY DEVELOPMENT DURING IMPULSE DRYING OF PAPER

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ABSTRACT

Impulse drying is a term coined for water removal from a moist paper web as it passes through a high temperature press nip. This new process produces heat transfer and water removal rates substantially higher than those attained in conventional drying processes. Increased energy efficiency, decreased capital costs, enhanced sheet properties, and increased utilization of high-yield furnishes are all likely advantages of the impulse drying process. Impulse drying results in the development of a unique density profile through the web thickness. This profile is characterized by a very high average value and a U or J shape, with the greatest density near the hot surface. Both the average density and the density distribution have an important influence on paper properties. This paper describes the mechanisms which lead to these density profiles and the experimental techniques used to identify them. Laboratory results indicate that density development in impulse drying depends on a number of driving forces not found in wet pressing or conventional drying. These include thermal softening, large total vapor pressure gradients, thermally-induced liquid phase dewatering, and others. This paper presents a mechanistic description of these densifying forces which is substantially supported by experimental measurements.

1. INTRODUCTION

In recent years, The Institute of Paper Chemistry has been investigating several new areas of drying technology which have the potential to dramatically alter the current papermaking process [1]. One of the most exciting and promising of these new areas is impulse drying. Impulse drying is the term coined for water removal from a high temperature press nip. The process involves intense dewatering and densifying mechanisms and is operative in the regime bounded by nip temperatures between 150-500°C, pressures from 0.3-7 MPa, and nip residence times up to 100-150 ms. In a performance overview of impulse drying, Sprague [2] presented some impressive experimental results: dewatering rates 100-1000 times those for cylinder dryers, specific energy use 1/3 to 1/2 that for conventional drying, and significant improvements in strength and other properties. The paper property improvements were strongly influenced by the density developed in the web.

In conventional paper manufacturing, most of the sheet density is developed in the press section through the action of mechanical pressing and fluid shear forces. In some cases, an asymmetric z-direction density profile is created in the sheet such that the flow exiting surface is most dense. This "stratification" process and its practical effects are discussed at length by MacGregor [3,4]. Theoretically, the density profile developed during pressing is retained as the fiber network continues to be bonded during drying. However, since fiber network recovery and rewetting are known to occur as the nip opens and since bonding proceeds under the action of surface tension forces with little mechanical restraint, the final density profile may be different from that developed dynamically. Impulse drying, in contrast, combines the two processes so that bonding occurs while under considerable transverse and longitudinal restraint so that the final density is more likely to resemble the density developed dynamically. In addition, the drying stresses that are developed probably have a strong influence on the strength properties of the sheet.

Impulse drying results in high average density values and in very nonuniform z-direction density profiles. The densifying forces create a J or U shaped profile, with the greatest density near the hot surface. The experimental work presented in this paper was initiated to investigate development of these density profiles, and to determine the mechanisms responsible. These mechanisms were identified and discussed in general terms in Sprague and Burton [5]. The purpose of this paper is to examine them in greater detail and to describe the unique experimental methods used in the investigation.

2. EXPERIMENTAL

2.1. Impulse Drying Simulation

Impulse drying is an extension of wet pressing in which one of the press rolls is elevated to a high temperature. Hence, a simple wet pressing simulator, operated with one heated pressing surface, suffices for the study of impulse drying. The press, known as a Wahren-Zotterman falling-weight press-nip simulator [6,7], was shown in a

comparative study to accurately duplicate press nip impulse characteristics [8]. Operation of the apparatus is simple; a platen, released from a specified height, falls and impacts a wet sheet/ felt combination to compress it against a stationary pedestal. The platen rebounds and is caught by a brake system to prevent a second impact. The resulting pressure-time relationship is typical of that seen in a roll press nip. This relationship may be altered by adjustment of the drop height and weight or by the choice of elastic material placed in the pedestal.

Figure 1 is a schematic of the impulse drying heads used in this study. The upper head is electrically heated and designed for temperatures up to 500°C. It is instrumented with a vapor pressure transducer and a fast response coaxial surface thermoprobe. The thermoprobe serves the dual purpose of temperature control and measurement of the instantaneous surface temperature for heat flux calculations. The pressure transducer measures the vapor pressure at the hot surface/ paper interface.

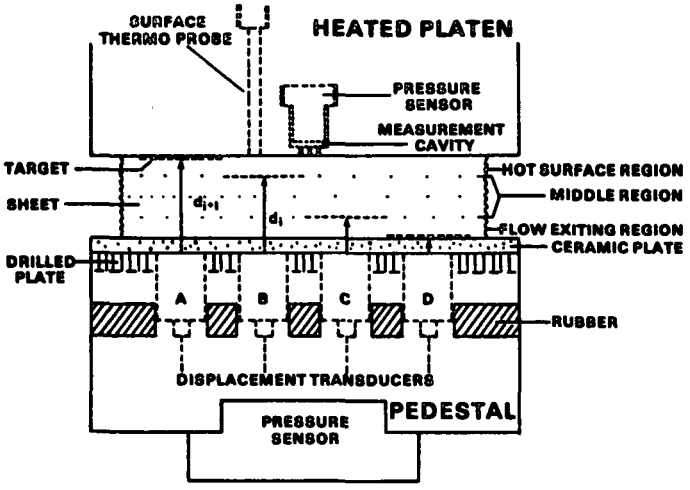

Figure 1. Schematic of heads used in impulse drying simulation.

The lower head (pedestal) is fixed and supports the web as the falling head compresses it. Water is expressed from the web into a ceramic flow receiver which has an average pore size of 40 μm. A vented drilled plate under the ceramic accepts excess water. The pedestal is instrumented with a force transducer which measures the impact force of the falling upper head, and four displacement transducers which provide data necessary for the determination of the sheet density profile.

Two separate data acquisition systems were used. Signals from the displacement transducers and sheet thermocouples were acquired with a Tracor Northern TN-1710 system, while signals from the surface thermoprobe, vapor pressure transducer, and force transducer were acquired with a Tec Mar A/D system. Both systems were interfaced with an Apple computer for data storage and manipulation. All data were eventually stored on a Burroughs B6900 mainframe for further plotting and analysis. Data collection by both systems was initiated simultaneously by a magnetic sensor activated by the falling carriage.

2.2. Dynamic Density Determination

A schematic in Figure 1 shows a magnified view of the special handsheet required for this study. During impulse drying, the heated platen compresses the wet sheet against the ceramic flow receiver. Special open-mesh targets, embedded in the sheet at various levels during forming, move with the fibers in response to the action of dewatering and densifying forces. The target motions are individually tracked by displacement transducers rigidly mounted beneath the ceramic plate. Rigid ceramic was chosen instead of a felt to eliminate displacement measurement error associated with nonuniformities in felt structure and to avoid the additional complication of felt compressibility. The instantaneous apparent density of a given region, based on dry fiber, is calculated from adjacent target separation and the known basis weight of the region, such that:

$$\rho_i = W_i/(d_{i+1} - d_i)$$

Where, ρ_i : Apparent Density of the ith Web Region (g/cm^3)
W_i : Basis Weight of the ith Web Region (g/cm^2)
d_{i+1}, d_i : Distance to targets above and below ith region, respectively.

Typical raw displacement data are shown in Figure 2. The applied pressure is included for reference. Before the "nip" closes and after it opens the sheet is unrestrained, so the signals may not accurately reflect the true positions of the targets in the sheet. However, unfiltered raw displacement data, obtained with the sheet under restraint, have been shown to be very clean and reproducible. The transducers are accurately calibrated with a special micrometer.

A number of factors are critical to accurate density determination. These include target material and thickness, method of target embedding, basis weight variability, and parallelism between the pressing surfaces. A simple error analysis showed that nonparallelism between pressing surfaces was the largest potential source of error. Precise machining of all parts, careful balancing and guidance of the falling carriage, and control of the pedestal level were necessary to achieve an acceptable degree of parallelism at contact.

If the target thickness is too large, corrections have to be made to account for its presence in the fiber network. Thus, the ratio of target thickness to sheet thickness should be minimized. If the target thickness is too small and it changes in temperature, the displacement measurement may be in error. Increasing target thickness and correct choice of target material can improve the thermal stability of the measurement. Finally, the openness of the target should be large enough to minimize flow resistance and to reduce interfacial effects. Targets used in this study were

made of electroplated copper mesh, 0.0254-0.0381 mm thick, and about 65% open area.

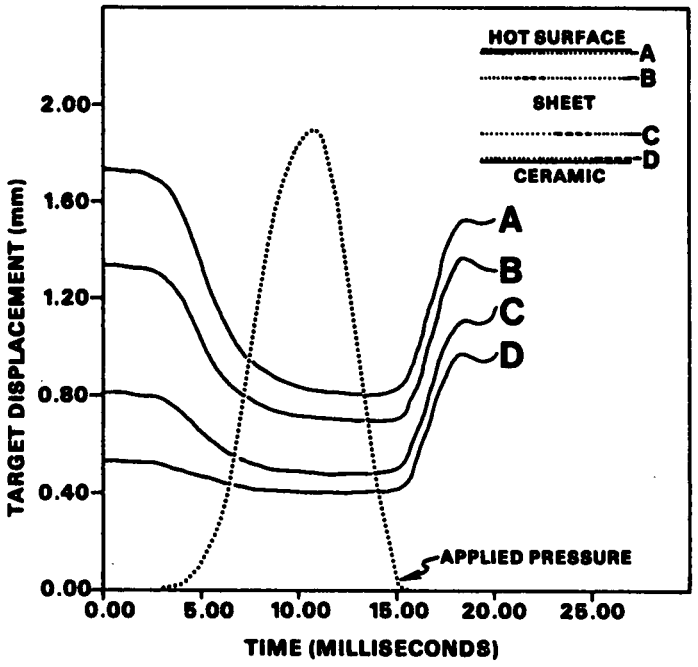

Figure 2. Typical unfiltered recordings of the target displacement histories (A-D) used in the calculation of dynamic density profiles, and the total nip pressure for wet pressing conditions at 20°C. P_{max} = 4.8 MPa.

2.3. Handsheet Formation

An unbleached, softwood kraft furnish at 0.005% consistency was used to form handsheets. Some of the pulp was beaten to 420 CSF while the rest remained unbeaten. All fines were removed from the unbeaten stock to give a freeness of 735 CSF.

A constant rate forming apparatus, similar to that described by Cowan [7] was used to form handsheets of basis weights ranging from 50 to 200 g/m^2. Forming of a handsheet was initiated by deposition of a known amount of fibers onto a forming tube septum. After all the fibers had settled, and in the presence of a continuous flow of distilled water, a target was positioned on the fiber mat surface. These steps were repeated until all targets had been embedded. Four targets were usually formed in the handsheet as illustrated in Figure 1. However, for basis weights of 50 g/m^2, only 3 targets were used to give a 50/50 basis weight split. This method produced handsheets of uniform and reproducible fiber distributions without the interfaces that develop when separate fiber mats are conjoined. After formation, the handsheets were lightly pressed between blotters to a target moisture content, stored overnight, and tested the following day. For tests which required internal sheet temperature measurement, however, it was necessary to conjoin individual fiber mats. Fine wire thermocouples (0.025-mm diameter) were placed between mats, and the resulting composite sheet was pressed to the desired moisture content.

3. RESULTS AND DISCUSSION

Impulse drying results in high average density values, even for small amounts of water removal. Sprague [2] reported increases over conventional processes of over 40%. Depending on the drying conditions, the average level of density developed "dynamically" during impulse drying is usually greater than for wet pressing. However, the manner in which that density is achieved is markedly different, as is the degree to which it is retained after leaving the nip. Figure 3 shows a comparison of the average sheet densities obtained during wet pressing at 20°C and impulse drying at 315°C. With the exception of hot surface temperature, the tests were performed under similar pressing conditions. Both cases show similar density development in the initial stage of compression. As compression proceeds, however, the impulse dried sheet densifies at a much higher rate and continues to densify until a maximum density is reached slightly before the peak mechanical pressure. After peaking, the sheet density levels out until the applied pressure starts decreasing. The wet pressed sheet densifies to a maximum value corresponding to the peak mechanical pressure and subsequently expands as one would expect for such a low initial moisture ratio. In contrast, the impulse dried sheet expands over a short time interval and then rapidly increases in density as the applied pressure decreases to zero. These major differences in sheet density response arise from new and very intense dewatering and densifying forces, unique to impulse drying.

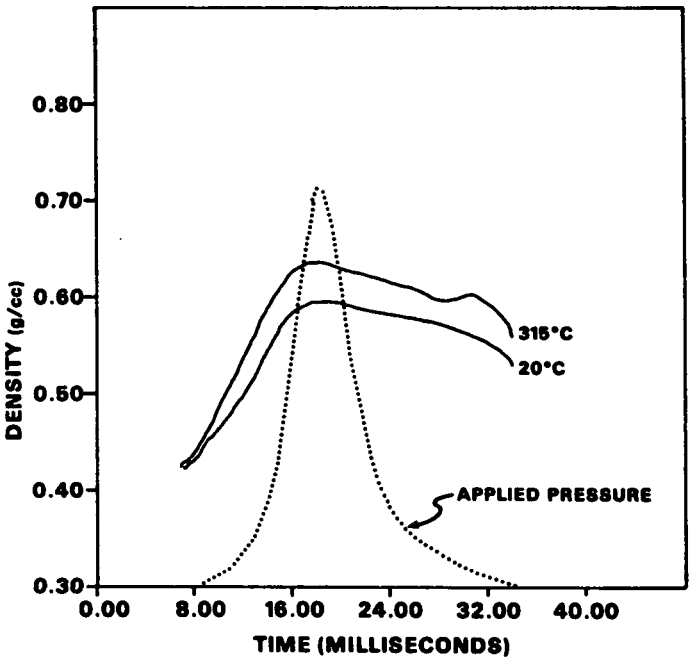

Figure 3. Applied pressure and the total sheet densities for impulse drying at 315°C and wet pressing at 20°C. Initial moisture ratio = 1.2, basis weight = 172 g/m^2, freeness = 735 CSF.

Measurement of the internal sheet temperature and z-direction density profile development have considerably increased our understanding of the dynamic physical processes which occur during impulse drying. Figure 4 shows density measurements for each of the three web thickness regions taken over a typical impulse drying event (also see Figure 1). Figure 5 and Figure 6 show local sheet temperature measurements and instantaneous heat flux to the sheet, respectively, for the same experimental conditions. In order to describe the densification process in detail, the impulse drying event has been divided into five time intervals numbered 1-5.

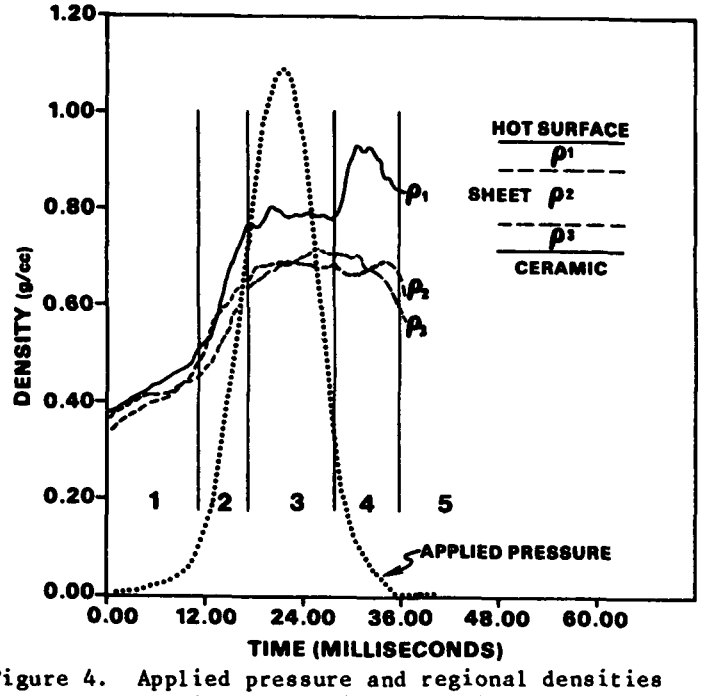

Figure 4. Applied pressure and regional densities for impulse drying of a fines-free unbleached softwood kraft sheet. Basis weight = 100 g/m^2, hot surface temperature = 260°C, initial moisture ratio = 1.3, freeness = 735 CSF. P_{max} = 3.8 MPa.

Interval 1 begins when the hot surface contacts the sheet. During this period, the initially unsaturated sheet densifies fairly uniformly throughout its thickness as it would in wet pressing. Temperature measurements (Figure 5) indicate that rapid sensible heating of the hot surface region of the web occurs at the same time. Because the sheet remains unsaturated, and at temperatures below the ambient boiling point over much of interval 1, there is little opportunity for liquid or vapor removal. Near the end of interval 1, however, the average temperature near the hot surface is well beyond the ambient boiling point, giving rise to a rapid increase in evaporation. The heat flux at this point is 0.568 MW/m^2 and rapidly increasing.

During interval 2, boiling at or near the hot surface rapidly produces water vapor which flows into the still unsaturated sheet. The vapor quickly reaches cooler sites where it condenses, raising the local temperature and degree of liquid saturation. The internal sheet temperature data suggest that this process moves progressively through the web, raising the temperature (T2 in Figure 5) much faster than could be supported by a conduction heat transfer mechanism alone. The evaporation/condensation process, combined wth the mechanical compression of the web, results in a liquid redistribution in which the lower regions become saturated with liquid water while the hot surface region remains predominantly filled with vapor. Internal temperature data show that this situation persists for the duration of the impulse. For faster pressure applications, liquid dewatering due to hydraulic pressure generation in the lower regions may occur.

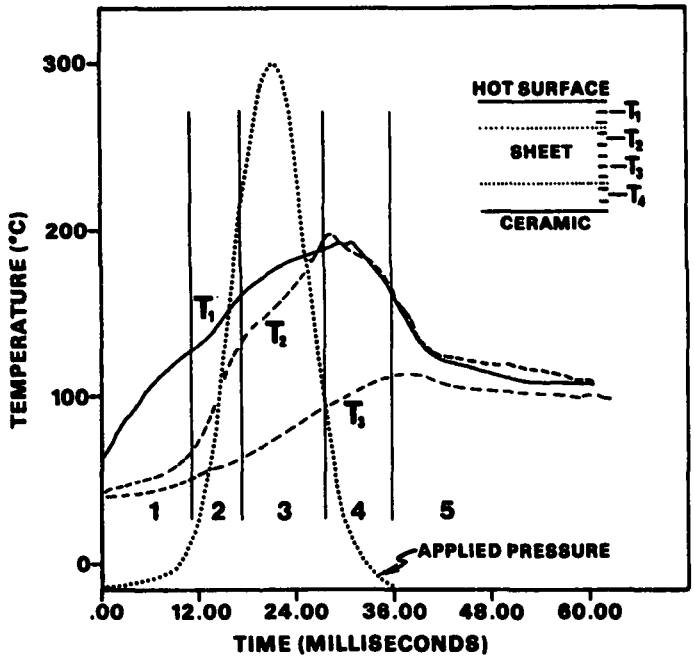

Figure 5. Applied pressure and internal sheet temperatures for impulse drying of a fines-free unbleached softwood kraft sheet. Basis weight = 100 g/m^2, hot surface temperature = 260°C, initial moisture ratio = 1.4, freeness = 735 CSF. P_{max} = 3.8 MPa.

Shortly after the start of interval 2, a new dewatering mechanism develops which is unique to impulse drying. Continued vapor generation combined with an increasing network flow resistance generates a substantial internal vapor pressure in the hot surface region. This vapor pressurization, acting on the liquid saturated lower region, induces liquid dewatering by liquid displacement. The onset of pressurization is detected experimentally by the hot surface vapor pressure measurement and by the appearance of hot surface region temperatures above 100°C.

The intense densification of the hot surface region during interval 2 results from the combined effect of increased mechanical compression, moisture redistribution, and thermal softening of fiber components. The middle and flow exiting regions densify under the action of mechanical

compression and vapor induced dewatering. The vapor pressure in the hot surface region continues to build and eventually reaches a level at which further densification is resisted. This point in time, which ends interval 2, corresponds to a peaking of the heat flux curve (Figure 6) and to a decrease in slope of the internal sheet temperatures. This is probably due to a combined effect of drying out of the region adjacent to the hot surface and an insulating effect of the vapor. Although the rest of the sheet continues to densify, the hot surface region density reaches a temporary maximum. This signals an end to interval 2.

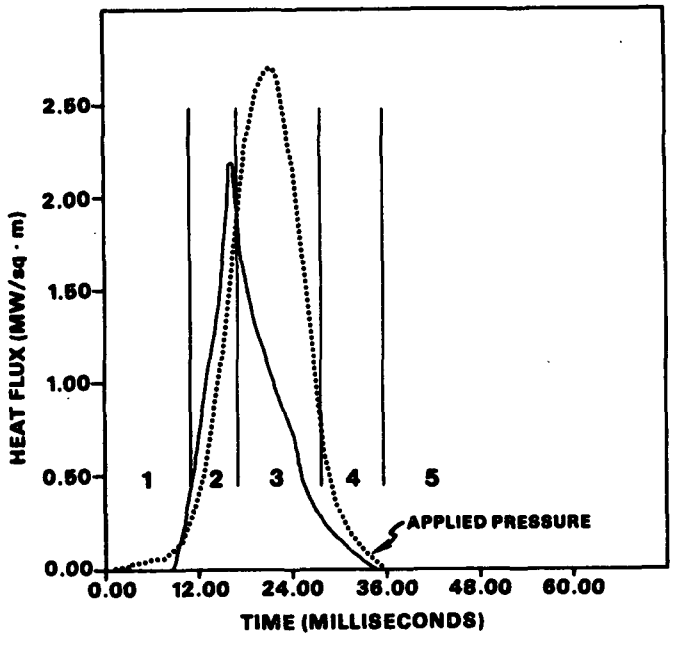

Figure 6. The instantaneous applied pressure and heat flux for impulse drying of a fines-free unbleached softwood kraft sheet. Basis weight = 100 g/m^2, hot surface temperature = 260°C, initial moisture ratio = 1.3, freeness = 735 CSF.

Although the moisture redistribution started in interval 2 tends to remove liquid from the upper region of the sheet, heat flux measurements for interval 3 indicate that sufficient liquid remains for evaporation to sustain the heat transfer required by the progressive heatup of the sheet. According to the temperatures measured in the web, vapor pressures as high as 1.25 MPa may be generated in the hot surface region by the end of this interval. Thus, sufficient pressurization should exist to prevent the hot surface region from further consolidation during interval 3.

Although the hot surface region density in Figure 4 remains relatively constant during interval 3, other experiments show that this region may experience a gradual increase in density. Even with the region predominantly filled with vapor, it is believed that a significant amount of water is still present in the cell wall. This water, at or slightly below the bulk temperature of the region, is difficult to remove due to the hygroscopic nature of the cellulosic fibers. The increase in hot surface region density over this period is thought to result from a progressive drying out of the region, particularly near the hot surface. A rapidly decreasing heat flux supports this interpretation. The flow exiting region, which is liquid saturated at a temperature less than 100°C during interval 3 reaches a maximum density under the action of mechanical compression and vapor induced dewatering.

As the applied pressure decreases, it reaches a point where it can no longer sustain the vapor pressure. The resulting decrease in internal vapor pressure creates a condition in which the fiber network must take up a greater share of the applied pressure. In addition, the pore water existing in the cell wall becomes superheated and flashes, allowing the pore structure to collapse. Hence, the fast rise in density of the hot surface region at the onset of interval 4 is thought to result from increased mechanical compression and cell wall collapse associated with reduced vapor pressure and pore water flashing. This unique densifying mechanism is supported by a rapidly decreasing bulk temperature of the hot surface region. The same process is seen to occur to a lesser extent in the middle region, although lagging in time. Further heating of the lower regions probably results from continued condensation of low-pressure vapor and conduction from the upper hotter regions.

After the applied pressure is removed, the onset of interval 5, evaporation and vapor release from the sheet are believed to continue for some time. This is indicated by the sheet temperatures at or above 100°C after the pressure has been released. For very intense drying conditions, this has been seen to result in delamination of the fiber network. However, under controlled conditions, this post-nip vapor release process is believed to contribute to the bulkiness of the middle region. The bonding which develops during the closed-nip portion of impulse drying is sufficient in most cases to maintain sheet integrity during vapor release.

The z-direction density distribution observed in the sheet after impulse drying usually closely resembles that observed dynamically during impulse drying. Hence, the bonding that develops under the considerable restraint of impulse drying, especially in the hot surface region, is not lost in post-nip processing. The profile is typically J or U shaped with the hot surface region having the highest average density followed in magnitude by the flow exiting region. The middle region, viewed under the scanning electron microscope (SEM), has a greater occurrence of interfiber voids and a lower degree of fiber collapse, which are believed to result from the post-nip vapor release process. In contrast, the hot surface region appears to be highly bonded with a high degree of fiber collapse. This unique distribution has been verified qualitatively by a SEM mapping technique [10] and quantitatively by a sheet grinding technique [11]. The specific distribution depends on the operating conditions in the nip, such as hot surface temperature, applied pressure and nip residence time, and also on sheet

characteristics, such as initial moisture, basis weight, and freeness.

The average sheet density, as shown by Sprague [2], increases with pressure and thermal impulse, with thermal impulse being the most important variable. Thermal impulse is defined as the product of hot surface temperature and nip residence time. This increase in average density is usually associated with an increasing uniformity of the density profile. As the intensity of drying conditions is increased, the high degree of densification created in the hot surface region extends further into the sheet.

Sheet conditions have a considerable influence on density development. Increasing basis weight or lowering freeness tends to increase the sheet flow resistance. This results in the development of higher internal fluid pressure gradients which, in turn, result in a more nonuniform density profile. For a higher basis weight and a given set of impulse drying conditions, the hot surface region comprises a smaller percentage of the total sheet thickness. Thus, the overall density is more dependent on the bulkier regions of the web. Longer nip residence times are required to achieve high densities in the heavier sheets. Impulse drying is usually carried out at moisture ratios of 1.5 or less. Increasing the sheet moisture content generally reduces the effectiveness of impulse drying. As the moisture ratio is increased, more sensible heat is required to heat the liquid water and the compression behavior is more typical of that observed in wet pressing. Decreases in water viscosity and increased thermal softening enhance the wet pressing process in a manner similar to the hot pressing results obtained by Back [12].

Impulse drying is a new, exciting, commercially viable water removal process involving intense dewatering and densifying forces. This paper has dealt with the unique densification process that is driven by these forces. While the ultimate z-direction density distribution will depend on the specific impulse drying conditions, the major mechanisms believed to be active have been presented based on a typical set of experimental conditions.

4. SUMMARY

Impulse drying results in high average sheet densities and nonuniform z-direction density profiles. This density profile results from the combined action of mechanical compression, intense heat transfer, moisture redistribution, vapor induced dewatering, thermal softening of fiber components, and flashing of superheated water. The profiles are typically J or U shaped, depending on applied pressure, thermal impulse, sheet moisture, basis weight, or freeness, and whether the sheet is impulse dried on one side or two.

A special measurement technique for "dynamically" determining the z-direction density profile during impulse drying has been developed. While this technique has led to increased understanding of the intense physical processes that operate during impulse drying, it has also been quite useful in wet pressing studies.

In this paper, the density development during impulse drying has been presented by dividing the impulse drying event into five consecutive time intervals. In the first interval the sheet densifies uniformly under mechanical compression as rapid sensible heating of the hot surface region brings its temperature to the ambient boiling point. Liquid dewatering by mechanical compression may occur, depending on pressing conditions. In interval 2, boiling at the hot surface, followed by condensation further into the sheet raises the local temperature and results in significant moisture redistribution. Temperature measurements indicate that this evaporation/condensation mechanism progresses into the sheet with time. A new, intense mechanism is initiated during interval 2 as mechanical compression and continued vapor generation cause an internal pressurization leading to "vapor induced dewatering". In interval 3, the pressurization resists further densification of the hot surface region while the middle and flow exiting regions densify under mechanical compression and vapor induced dewatering. As the compressive pressure is reduced on the exit side of the nip, it reaches a point where it can no longer sustain the vapor pressure. This marks the beginning of interval 4. A rapid density increase in the hot surface region at this point is believed to result from a combination of reduced internal vapor pressure and from appreciable flashing of superheated pore water. As the vapor pressure is reduced and superheated pore water flashes, the cell walls collapse under a combination of surface tension forces and mechanical compression. In interval 5, evaporation and vapor release from the web continue as the applied pressure is removed from the sheet. This post-nip vapor release process leads, under controlled conditions, to a bulkier sheet interior.

The key new mechanisms identified by the measurement techniques described in this paper include moisture redistribution by an evaporation/condensation mechanism, a vapor induced dewatering mechanism, an internal pressurization mechanism which resists sheet compression, a complex mechanism which involves cell wall collapse due to vapor pressure release and flashing of superheated pore water, and a post-nip vapor release mechanism leading to expansion of the interior of the impulse dried sheet.

5. ACKNOWLEDGMENT

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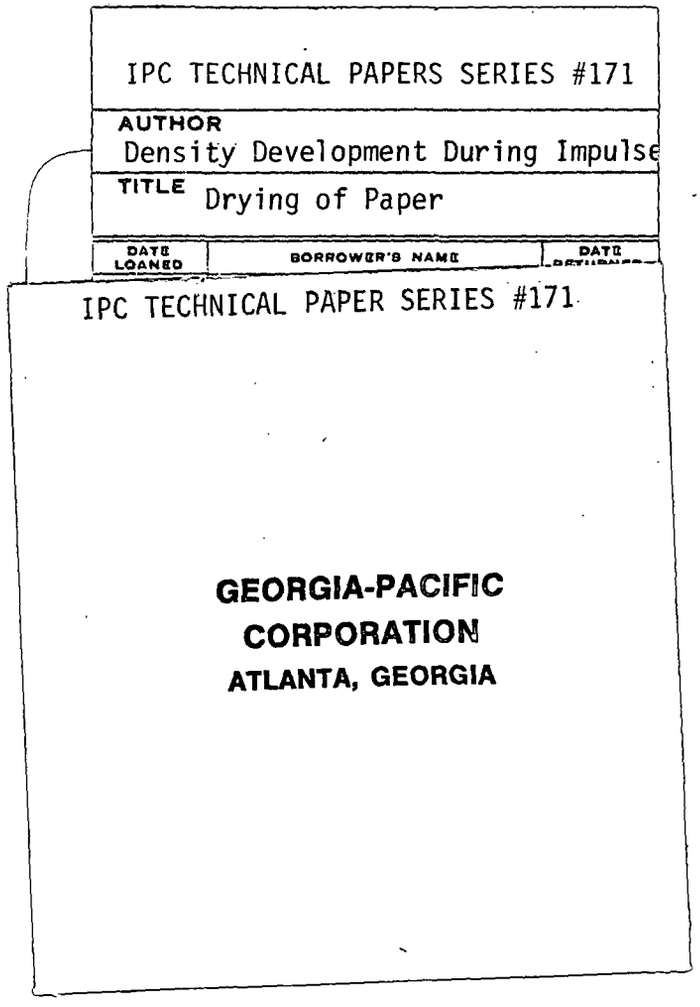
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